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Determining the Source Characteristics of Explosions Near the Air-Earth Interface

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Determining the source characteristics of explosions near the air-earth interface

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Abstract

We present a method to determine the source characteristics of explosions near the air-earth interface. The technique is an extension of the regional amplitude envelope method and now accounts for the reduction of seismic amplitudes as the depth of the explosion approaches the free surface and less energy is coupled into the ground. We first apply the method to the Humming Roadrunner series of shallow explosions in New Mexico where the yields and depths are known. From these tests, we find an appreciation of knowing the material properties for both source coupling/excitation and the free surface effect. Although there is the expected tradeoff between depth and yield due to coupling effects, the estimated yields are generally close to the known values when the depth is constrained to the free surface. We then apply the method to a regionally recorded explosion in Syria. We estimate an explosive yield less than the 60 tons claimed by sources in the open press. The modifications to the method allow us to apply the technique to new classes of events, but we will need a better understanding of explosion source models and properties of additional geologic materials.

1 Introduction

Due to its prominent role in nuclear explosion monitoring, seismology has long been interested in determining the source characteristics of underground explosions, such as yield and depth. Methods for determining the yields of contained events range from teleseismic amplitudes and P-wave spectra to regional P-waves amplitudes and coda magnitudes [e.g. *Douglas and Marshall*, 1996]. *Pasyanos et al.* [2012] developed a method to characterize underground explosions based on regional amplitude envelopes across a broad range of frequencies. One advantage of the method is that examining the signal over a wide frequency band can reduce some of the strong tradeoffs between yield and depth. Estimating the yield of uncontained events has likewise been a subject of research interest. For example, *Koper et al.* [2002] examine truck bombs by combining local seismic and acoustic data.

In this paper, we expand on our previous method to consider events near the air-earth interface that are not contained. We will first describe the extensions to the regional amplitude envelope method. Next, we will apply the technique to the Humming Roadrunner experiment in New Mexico, where the depths and yields of a series of explosions are known. In order to further demonstrate its applicability, we test the method on remote observations of an uncontained explosion from the Syrian Civil War recorded at regional stations in Turkey.

2 Method

The method we will be using for examining the source characteristics of near-surface explosions is an extension of the regional amplitude envelope method. This technique was developed, described in detail and applied to North Korean nuclear explosions in *Pasyanos et al.* [2012], then applied to chemical explosions and nuclear tests in Nevada in *Pasyanos* [2013]. In summary, the method takes an earthquake or explosion source model and corrects for the wave propagation through the media to generate predicted waveform envelopes at any particular frequency band. Sources of various sizes (magnitude or yield) and depths can be proposed and compared to the data over a wide frequency-band in order to select among the proposed models. By explicitly modeling both yield and depth, we don't make any assumptions about having a standard depth of burial, that is, a depth used for reliable containment.

Consistent with our previous work, for explosions, we use the Mueller-Murphy [MM] explosion source model [*Mueller and Murphy*, 1971], although some recent studies have suggested that the Denny-Johnson [DJ] model [*Denny and Johnson,* 1991] may be more applicable to shallow chemical explosions [*Stroujkova and Morozov*, 2014]. The MM model produces a P-wave moment spectrum by specifying a nuclear yield, a depth-of-burial, and an explosion source point material where the available materials are granite, tuff, salt, and shale [*Stevens and Day*, 1985]. As in our previous studies, we use the Fisk conjecture [*Fisk*, 2006] to specify the S-wave corner frequency and source amplitude levels for explosions. Stronger materials are better able to couple the energy into a seismic signal. For the chemical explosions considered here, a factor of two will be used to convert from a chemical yield to an equivalent nuclear yield [*Denny,* 1994].

The source is then propagated to observing stations by accounting for geometrical spreading, anelastic attenuation, and site effects to estimate the observed amplitudes of the primary regional (Pn, Pg, Sn, Lg) or local phases (Pg, Sg), depending on the distance. The regional attenuation structure is determined empirically using earthquakes. Coda decay parameters for a region, also determined empirically, are then combined with the direct phase amplitudes to construct synthetic waveform envelopes, which are then compared to the waveform envelopes of the data.

The depth input into the MM model can be any non-negative value although, in theory, the method would only be applicable to contained explosions. In order to extend the method to uncontained explosions, we must add a coupling factor that is a function of emplacement near the surface, which we call the free surface effect. *Ford et al.* [2014] studied the partitioning of energy between seismic and acoustic for near-surface explosions. In equation (1) from the study, they estimated the seismic displacement as:

$$\log_{10}(d_s) = \beta_1 + \beta_2 \log_{10}(r_s) + \beta_3 \tanh(\beta_4 h_s + \beta_5) \qquad (1)$$

where d_s, r_s, and h_s are scaled displacement, scaled distance, and scaled height-of-burst (all scaled by the cube-root of event yield) and β_{1-5} are empirically regressed values, which depend on the media. *Ford et al.* [2014] reported β_{1-5} for explosions in alluvium, the values of which are provided in **Table 1**.

At infinite depth as $h_s \rightarrow -\infty$, and $\tanh(\beta_4 h_s + \beta_5) \rightarrow -1$, the scaled displacement becomes

$$d_s' = 10^{[\beta_1 + \beta_2 \log_{10}(r_s) - \beta_3]} \tag{2}$$

Substituting this back into equation (1) and simplifying, we find

$$d_s = d_s' \ 10^{\beta_3[\tanh(\beta_4 h_s + \beta_5) + 1]} \tag{3}$$

In other words, the scaled displacement at any depth will be a function of its fully contained value (d_s'), its scaled height-of-burst and empirical values $\beta_{3\text{-}5}$. This results in a factor of 3 reduction in alluvium [*Ford et al.*, 2014]. A factor of 12 reduction in hard rock was found from the analysis of explosions in limestone at Kirtland Air Force Base, New Mexico, where β_3 is estimated to be -0.55 (**Table 1**). We will use equation (3) to scale the predicted amplitudes of uncontained explosions from fully-contained explosions. As the amplitudes of the fully contained explosions will continue to decrease with increasing depth, we calculate the fully-coupled amplitudes using the values at a scaled depth of 120 $(W)^{1/3}$ m, where W is yield in kt. At these depths, the MM and DJ models are most consistent although there are differences in the predicted corner frequency.

In the original method, we have sensitivity to the depth-of-burial since the amplitude at each frequency depends on a combination of both yield and depth, and these alter the event corner frequency. Analysis of waveforms at various near-surface heights and depths showed that there is very little, if any, change in corner frequency for the small (sub-kiloton) events considered here, so the free surface effect is applied to the amplitudes of all phases at all frequencies. This results in a non-uniqueness between depth and yield in our solutions.

3 Humming Roadrunner Explosions

The Humming Roadrunner (HRR) experiment was a series of large surface explosions conducted at the White Sands Missile Range in New Mexico in 2012 (**Figure 1a**). The events ranged from 10-50 tons equivalent TNT. Five of the six shots were detonated on the free surface, while the 20 ton HRR-2 shot was exploded in a tunnel. HRR-1 (20 tons) and HRR-5 (50 tons) were conducted in granite, HRR-3 (10 tons) and HRR-4 (10 tons) in alluvium, while HRR-6 (50 tons) was conducted in alluvium of 11 m depth overlying granite [*Bonner et al.*, 2013].

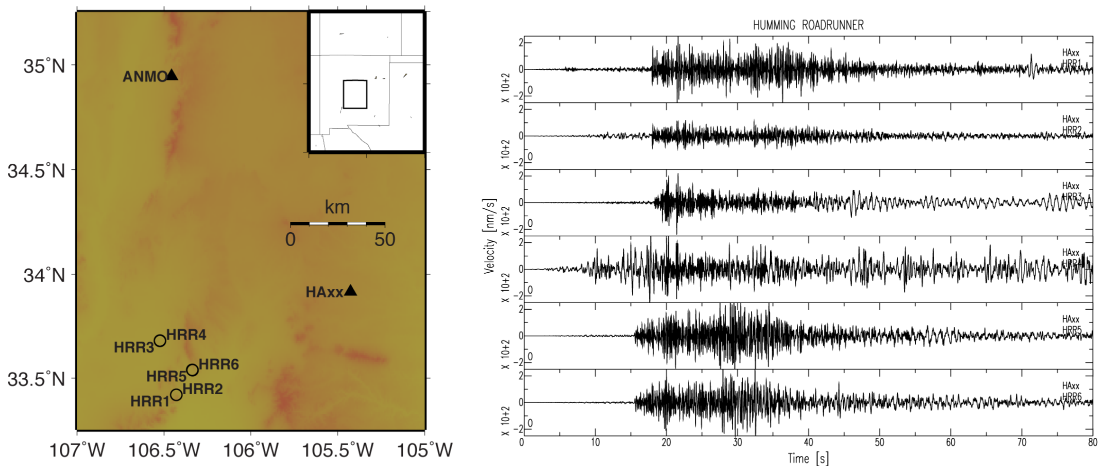

Figure 1. Elevation map of study area for the Humming Roadrunner explosion series, along with recorded seismograms of the events recorded at station HAxx. Waveforms have been filtered between 1 and 10 Hz.

All shots were recorded at station HAxx, about 100 km to the northeast (**Figure 1b**) and station ANMO about 200 km due north. For the shot point, we use granite specified in MM for the granite shots. As alluvium is not specified in the original MM formulations, we follow the suggestion of *Murphy and Bennett* [2010] and scale the source spectrum of tuff by 6.5. We use the free surface effect of *Ford et al.* [2014] for the alluvium and the hard rock free surface effect for the granite shots. Attenuation values for the western U.S. come from *Pasyanos* [2013] and coda parameters for the region are provided by Rengin Gök [personal communication].

We first consider HRR-1. In all cases, we use signals recorded at stations HAxx and ANMO for four frequency bands between 1 and 8 Hz. In **Figure 2**, it is easy to observe the tradeoff between yield and height-of-burst/depth-of-burial. This is an expected feature of the method. Deeper, well-coupled explosions have seismic signals equivalent to larger uncontained explosions near or above the free surface, and can be difficult to distinguish using seismic data alone. Purely based on RMS misfit, we would estimate a yield of 1 ton chemical at depth. If we made use of information that it was on the surface, we would estimate the yield as just slightly less than the true yield of 20 tons (open star).

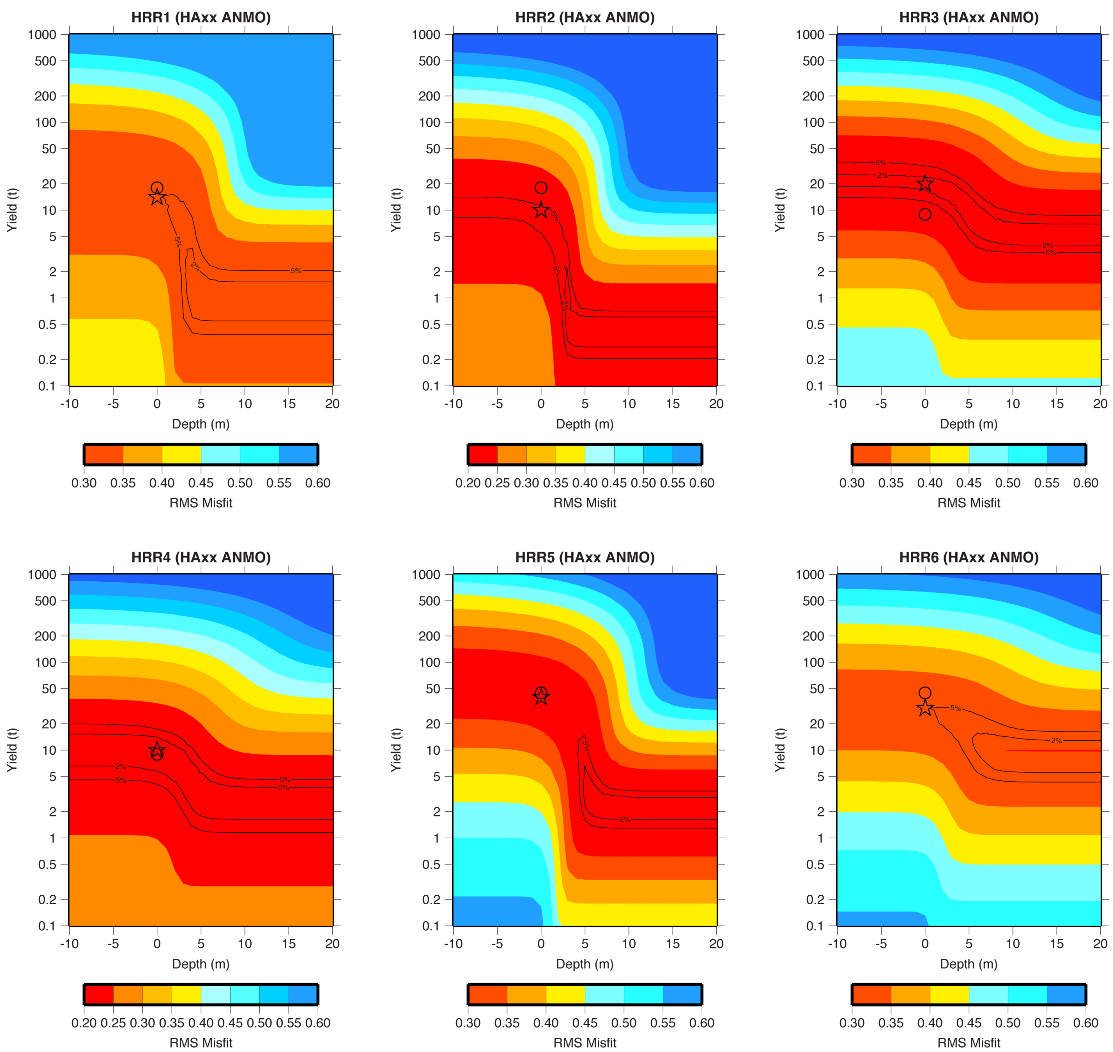

Figure 2. Misfit as a function of explosive chemical yield and depth-of-burial/height-of-burst for events in the Humming Roadrunner explosion series. Colors indicate the level of misfit. The minimum RMS at the free surface is indicated by the open star. True values are indicated by the open circle. Contours show percentages above minimum RMS.

The effect of yield on the predicted envelopes and hence the sensitivity of the method to estimating yield is illustrated in **Figure 3**. In this figure, the envelope data (shown in blue) is compared to yields of 2, 5, 10, 20, 50, 100, and 200 tons for one station and passband. While the estimated yield of 20 tons has the minimum misfit, the envelopes can be comparably fit by slightly higher or lower yields and the collective fit can be improved by including more stations and passbands.

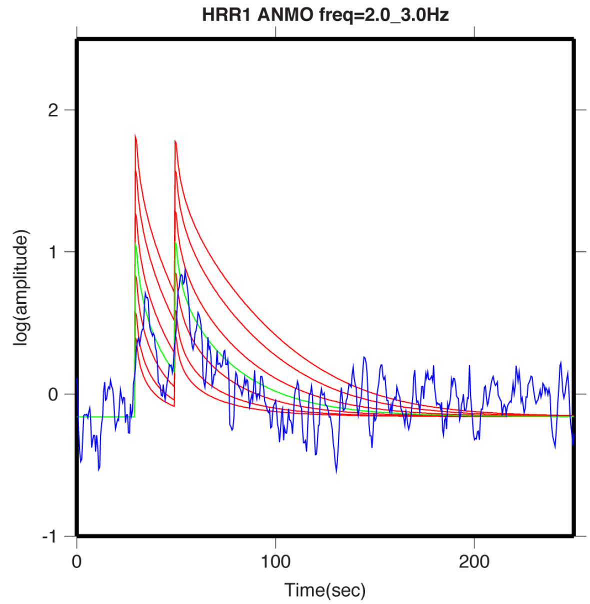

Figure 3. Envelope fits for HRR1 at station ANMO in the 2-3 Hz passband at the surface (z=0) for chemical yields ranging from 2-200 tons (red and green lines) to the data (blue line). The estimated yield of 20 tons is shown in green.

We see a similar tradeoff between yield and depth for the other events in the sequence (**Figure 2**). For HRR-2, we estimate a yield of 10 tons at the free surface, which is lower than the actual yield of 20 tons, but this is the shot that was conducted in a tunnel, and may exhibit some decoupling of seismic energy [*Latter et al*., 1961] as a result. Notice the lower amplitudes for this shot at HAxx compared to HRR-1 (**Figure 1b**). For HRR-3, we overestimate the yield, whereas for HRR-4 we have an almost exact match. This is unusual, as the two events are very similar except that the noise level was significantly higher for HRR-4 (**Figure 1b**). Observe as well the smaller free surface effect for these two shots in alluvium.

The yield of HRR-5 is well-recovered at 50 tons. HRR-6 was underestimated at 20 tons (vs. 50 tons actual) which is interesting because the signals look almost identical to HRR-5 (**Figure 1b**). The estimate differs because we used alluvium for the actual alluvium-over-granite geology, rather than the granite used for HRR-5. If we instead use granite, then we would again recover the correct yield. In all of the cases considered, we find yields around the known values at the free surface. Where results vary from the true yields is attributable to material properties and coupling.

4 Syrian Explosion

Explosions in the Syrian Civil War have provided events of opportunity to apply and evaluate the method to characterize events near the air-earth interface. One method increasingly used by opposition forces in the conflict is to clandestinely dig tunnels under government facilities and detonate the explosives directly under target. In mid-May 2014, after reports and video footage of an explosion (http://www.nydailynews.com/news/world/syrian-rebels-blow-army-base-major-hit-assad-article-1.1793271), Syrian rebels claimed to have dug under the Wadi al-Deif military base and detonated 60 tons of explosions. The base is located about 2 km east of the city of Maarrat al-Nu'man in northwest Syria (**Figure 4a**). Rebels reported that they dug an 850 m long tunnel, although the depth of the tunnel under the free surface was unclear.

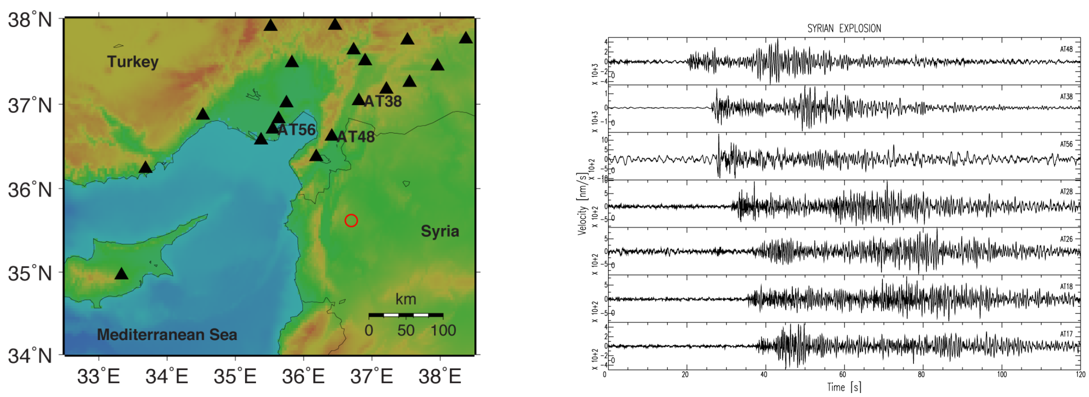

Figure 4. Elevation map of study area for Syrian explosion, along with recorded seismograms for the event. Red circle indicates the event location. Waveforms have been filtered between 0.5 and 8 Hz.

The event occurred on May 14, 2014 and appeared in the EMSC and KOERI catalogs as M_L=2.9 (KOERI) and M_L=2.8 (EMSC) although both catalogs reported a non-surface depth (7.8 km KOERI, 10 km EMSC). Although we did not have access to seismic data from Syria, it was well recorded by regional stations in Cyprus and Turkey, including data from Continental Dynamics: Central Anatolian Tectonics (CD-CAT) project [*Whitney et al.,* 2012]. **Figure 4b** shows waveforms from CD-CAT stations at epicentral distances less than 250 km, but the signal is clearly observable out to 500 km and beyond.

Our first task in studying this event is ascertaining the material properties of the region. The Geological Map of Syria [*Ponikarov*, 1986] describes the geology of the area as Paleocene, specifically Middle Eocene, age and characterized as "soft, chalky, and firm mumulitic limestones, marls." For purposes of the shot point, the closest MM material for limestone is tuff. We use the hard rock free surface effect, as being more applicable to limestone than alluvium. Attenuation values for the Middle East come from *Pasyanos et al.* [2009] and coda parameters for the region are provided by Rengin Gök [personal communication].

Since the event was well-recorded by the CD-CAT deployment, we use data from the three closest stations (AT38, AT48, AT58) in the inversion, with the misfit shown in **Figure 5**. If the explosion occurred well above the surface, a yield of 100 tons TNT equivalent would be required to produce the observed seismic signal. At the free surface, a yield of 60 tons is needed (open star). If the event was fully coupled, the yield might be as low as 1 ton. Given the video footage of the explosion, however, we know that it was neither at nor above the free surface, nor fully-coupled. We estimate a chemical yield ranging from 6 and 50 tons depending on the depth, with the best estimate between 20-40 tons. Including independent information on the depth, we could narrow this considerably. If, for instance, we definitively knew that the explosion occurred at 2 m below the surface, then we would estimate the yield at 40 tons.

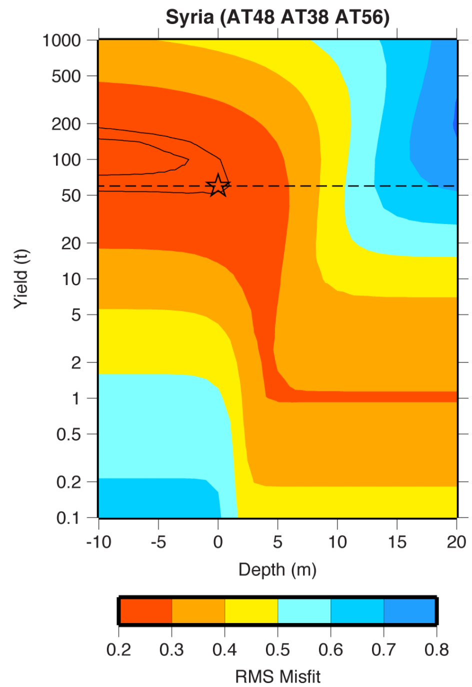

Figure 5. Misfit as a function of yield and depth-of-burial/height-of-burst for the Syrian explosion. Colors indicate the level of misfit. The minimum RMS at the free surface is indicated by an open star. The yield claimed by the rebels is indicated with a dashed line.

While this seems considerably less than the 60 tons claimed by the rebels, there could be a number of reasonable explanations. The first is simply that the amount of explosions used was exaggerated or over-reported by the rebels. Another explanation is that the energy density of the explosives used, reported to be a locally made explosive, is less than that of TNT, in which we are reporting equivalent chemical yield. The relative energy density of ANFO (ammonium nitrate fuel oil), for instance, varies depending on the metric used (e.g. impulse, pressure, energy), but is generally about 0.8 that of TNT [*Sochet et al.,* 2011]. Homemade explosives could be considerably less. It is also possible that the explosion was not a complete denotation of all of the explosive material. Given these considerations and additional uncertainties in the material properties of the region, our estimate for the yield seems to be reasonable.

5 Conclusions

We have extended the regional amplitude envelope method away from its assumption of the source being a contained explosion, and applied the new method to several explosions of interest in New Mexico and Syria. While we observe the expected tradeoffs between yield and depth/height, when constrained by other information, we find yields consistent with ground truth yields in New Mexico and reasonable values from what we know in Syria. Combining seismic with atmospheric overpressure signals can help break the tradeoff between yield and height-of-burst [*Koper et al.,* 2002; *Ford et al.,* 2014].

Using this method in this and previous papers, we have been able to examine chemical explosions ranging from 10 tons up to 1 kt for the Non-Proliferation Experiment (NPE) chemical kiloton shot, and nuclear explosions (from North Korea and Nevada) from less than 1 kt to 150 kt, from local (<100 km) to regional (>400 km) distances, and from fully contained explosions to shots at the free surface. By allowing the methodology to consider shallow, uncontained events just below, at, or even above the air-earth interface, we make the method relevant to new classes of events including mining events, military explosions, plane crashes, or potential terrorist attacks. Successful application of this method to other events will depend on a more solid understanding of the material properties (coupling and free surface effect) for a wider variety of geologic materials.

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Tables

Table 1. Coefficients of equation (1) for alluvium [*Ford et al.*, 2014] and hard rock.

Coefficient	Alluvium	Hard Rock
β_1	-3.39	-3.73
β_2	-1.74	-1.74
β_3	-0.22	-0.55
β_4	4.84	4.84
β_5	1.23	1.23

Figure Captions

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